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Automotive Manual Transmission Gear shift Performance Improvement by Synchronizer Design

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Keywords: Synchronization time, Shift Feel, Cone torque and Index Torque

Introduction: In 4000 BC Mesopotamian vase had shown a glimpse of cart design, leading the development of wheels by wooden disc in 2500 BC resulting EULER / Watt to propose the theory of gear box in automotive world. The German motor industry produced 4,90,581 vehicles including cars, vans, trucks, buses and tractor-trailer units. In 1992, production had reached 5.2 million vehicles. In manual Transmission, shifting between gears is solely controlled by driver through shifting mechanism, either cable shift mechanism or floor shift mechanism. Thus gear shifting mechanism also plays a critical part in synchronization process with respect to comfort of driver.

Types of Internal gear shifting mechanism:

a. Sliding gear
b. Dog clutch engagement
c. Pin engagement
d. Synchronizer without locking mechanism
e. Synchronizer with locking mechanism
f. Servo lock synchronizer mechanism (Porsche system)
g. Hydraulically activated multi-plate clutch for power shift transmission
h. Hydraulically activated multi-plate brake for planetary gear

Types of External gear shifting mechanism:

a. Floor shift mechanism’
b. Cable shift mechanism

Transmission Design & Engineering has been primarily focused on design for Performance (Noise, Shifting and Fitment on vehicle tunnel) along with Serviceability, Manufacturability and Cost optimization. So, while the conceptualization phase of any new transmission design VOC (voice of customers), gear shifting feel and perception have a major influence on perceived comfort.

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Objective: In this paper, the experience for Gear shift improvement with change in appropriate Synchronizer design (Dimensional parameters, frictional area and friction coefficient etc), aligning with customer requirement of performance, serviceability and cost while translating customer expectation into design and development of Automotive manual transmission.

Description: The function of synchronizer is to provide exact friction load for reducing the relative motion /velocity /RPM of clutch gear and output shaft in stipulated time without the feel of delay or jerking while changing from Gear-1 to Gear-2 during driving or coasting condition of vehicle.

Stages of synchronizer:

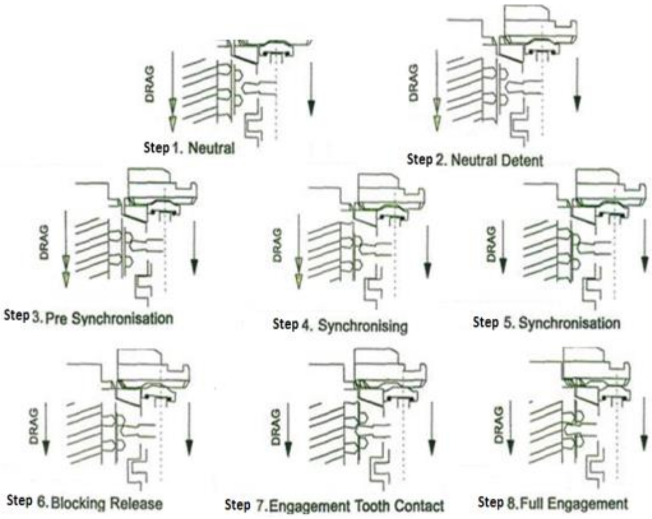

Fig 1: Stages of synchronization

Step 1: Neutral Gear condition

Step 2: Neutral detent

Step 3: Pre-synchronization

Step 4: Synchronizing

Step 5: Synchronization

Step 6: Block ring Release

Step 7: Engagement tooth contact

Step 8: Full engagement

Types of synchronizer:

1. Cone Synchronizer(Multi layer and plate synchronizer): During a gear shift, the force is acting by vehicle driver constantly through gear shift mechanism(either cable of floor) to spring loaded insert clutching arrangement for the engagement of blocker ring with Synchro cones (the only condition to be adhere is the cone torque should be higher than index torque) .
   a. Brass synchronizer (Axial and radial Synchronizer)
   b. Friction material coated synchronizer

The multi cone surface provide more interfaces, which leads the reduction of shift efforts at ball knob with higher cone torque by optimum cone angle , considering improvement in axial wear parameters amount.

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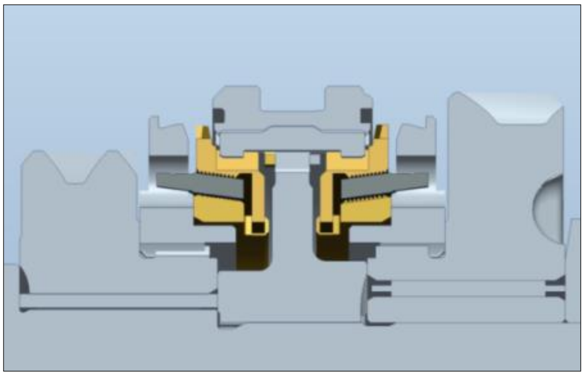

Fig 2: Synchronizer layout

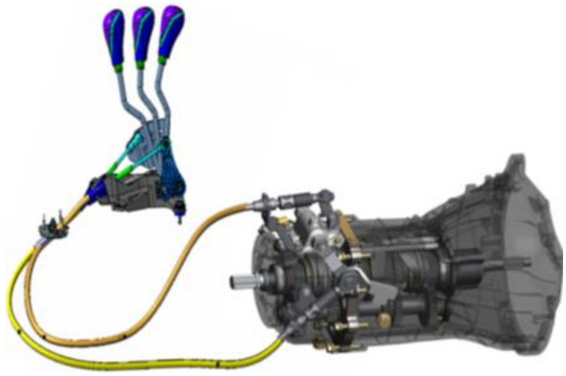

Fig 3: Gear shifting layout

2. Servo Synchronizer: This type of synchronizer is commonly used in Porsche designs. The idea behind the synchronization is same as internal expanding drum brakes. The movement of selector sleeve towards a gear leads to contact made with split ring, which is connected with gear directly, creating friction between sleeve and the split ring causing synchronization process and when the relative rpm tends to zero, leads to the complete engagement of gear.

3. Pin synchronizer: The pin loading synchronizer is basically blocking synchronizer which plays the synchronization process through the tapper portion of the pin.

Empirical formula for Analysis:

Gear shifting of a manual transmission is function of four factors i.e. Synchronization time ,shift force, shifting mechanism leverage and shift travel which are further classified or dependent on the variables like Cone torque, coefficient of friction, cone angle, index angle ,frictional area, gauge radius, drag torque etc

Gear shifting in Transmission $f(x)$ {

Synchronization Time (Ts)
Shift force
Shift Travel
Shift mechanism Leverage

} $f(x_1)$ {

I_R = Reflected Rotational Inertia
μ =Coefficient of friction
Tc =Cone Torque
Rc =Mean cone radius
Ø = Cone angle
A =Frictional Area
Ti =Index Torque
T_D = Drag Torque

}

Formulae for Cone Torque:

$$T_c = I_R \alpha_G \pm T_D$$

$$T_c = \frac{F \mu_c R_c}{Sin(\phi)}$$

Formulae for Index Torque and Synchronization time

$$T_i = \frac{FR_B(Cos\frac{\Theta}{2} - \mu_b Sin\frac{\Theta}{2})}{(Sin\frac{\Theta}{2} + \mu_b Cos\frac{\Theta}{2})}$$

$$Ts = \frac{(\omega_2 - \omega_1) I_R}{T_{c(avg.)}}$$

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Results: The authors have design and implicated the multi-cone synchroniser as well as synchroniser with friction material and successfully achieved the results demanded by customer for Automotive Manual transmission for shift performance improvement.

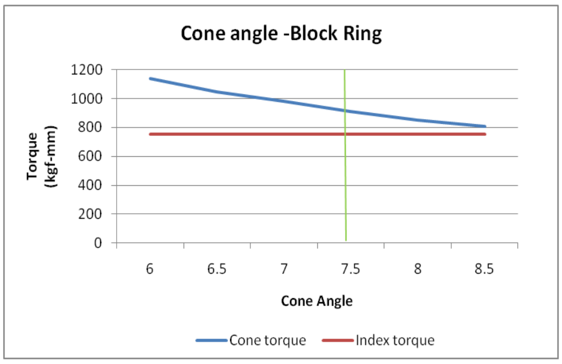
Experimental results & CAE results in the synchronizer action at different level of friction coefficient and frictional cone area of mating surfaces for better shift feel, shift force and overcoming bumpy observations during shifting are derived for sample case in Fig 4, Fig 5 and Fig 6.

Cone Torque: Generally known as synchronization torque, is the result of the friction force between the conical surfaces in the synchronizer.

Index Torque: Arises from the shift sleeves chamfered teeth applying an axial force on Synchro cone chamfered teeth. Index torque always opposes the cone torque.

Key findings for god synchronization are that cone torque must be higher than the index torque at all times during the synchronization to ensure blocking of axial shift sleeve motion.

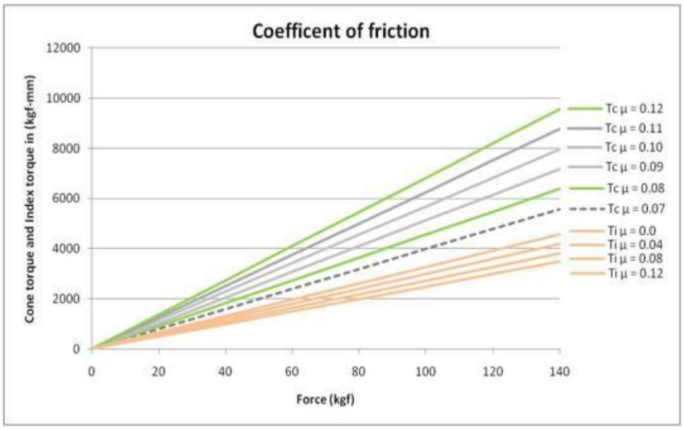
The percentage increase of cone torque and index torque is stabilized by CAE estimation and validation on Test-rig and vehicle testing to have the best shift feel for customers.



Fundamentally the cone torque should always be higher than index torque for proper synchronization without clash or seize of block rings. Generally the cone angle used is in the range of 6 to 8.5.But the cone angle less than or equivalent to 6 have the tendency to seize or stick, even the cone angle higher than 8 has limitations for selection of cone torque and index torque.

Fig 4: Variation of Cone angle w.r.t Torque

Arriving to the relation of cone torque and index torque is by the experience of designer on drawings platform well as vehicle running conditions to get the maximum desire satisfaction to the end user with respect to the shift feel rating of best in class.



The coefficient of friction of blocker ring and sleeve, cone torque, index torque and handball force are interdependent variables. For a particular application the selection of friction material is to be derived through the shown plot in Fig 4. The higher the COF, higher cone torque can be obtained with lesser shift force. Similarly the higher COF will provide lesser index torque at lesser shift force.

Fig 5: Impact of COF on shift force w.r.t Torque

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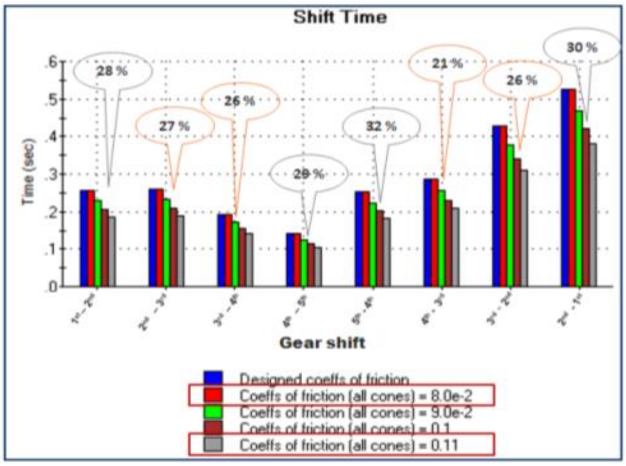

Fig 6: Shift time variation with friction coated

The design coefficient of friction carbon has been validated through CAE Romax software and the synchronization time for the shifting from gear-X to gear-Y has been shown in the fig 5 .which results in 26% decrease in synchronization time, while in up shift (4th to 5th Gear) and in down shift (5th to 4th Gear) the decrement is 32%.The friction coated blocker ring leads to reduction in synchronization time up to 26%-29% in up shift and 21%-32% in down shift for the better shift feel.

The design & validation had proved out through formulae calculation, validated with CAE simulation, test-rig validation and vehicle validation by analyzing the synchronization time and shifting forces with optimizing shift feel of through customer feedback.


Fig. 7: Test Rig for Synchronizer Testing

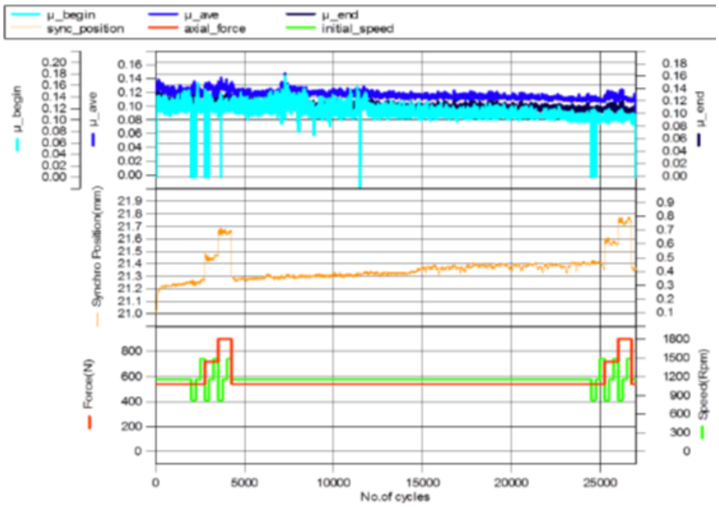

Fig. 8: Test Rig results of COF

The design synchronizer are then validated physically through synchronizer Test –rig (SSP 180 German) through durability and performance testing cycle (up to 25K shift cycles) shown in fig 8.
This has been validated and proved out for passenger and commercial vehicles (LCV) transmissions with respect voice of customer.

The improvement in shift force is 25-30% (By using friction carbon coated single Blocker rings) with the Shift feel rating is 2-3 on the scale of 5, 30-40% (increasing the number of frictional surface area i.e. Dual-cone Synchronizer) with the Shift feel rating is 3-4 on the scale of 5. This improvement can be further increased the further increase in friction surface (usage of Triple cone or combination of dual cone with Friction coated blocker rings).

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Conclusion:

Major parameters considered during design and analysis for synchroniser performance are Cone torque, Index torque Leverage which are the function of Clutch inertia, Reflected inertia, Cone angle, Cone geometry, Gear sleeve and hub geometrical parameters, oil spec, etc.

The important aspect in business is to capture the VOC (Voice of customer) for expectation of shift feel bench mark, Cost, engine torque- drivability conditions (Gear ratio required for accelerations) and space available inside transmission to accommodate synchroniser diametrically as well as radially, Lever ratio to suit ergonomics etc by engineering the best suitable synchronizers design of single Cone or multi-cone with or without friction material.

The voice of customer has been translated from drawing to design and validated with respect to the Performance (Noise, Shifting and Fitment on vehicle tunnel) along with Serviceability, Manufacturability and Cost optimization up to the customer requirement.

Generally for higher torque gear ratio (i.e. 1st and 2nd Gear), the usage of dual cone is better as comparing single cone brass rings.

While for higher speed / RPM gear & more usage Gears (i.e. 3rd, 4th and 5th Gear), the friction coated blocker rings are the best possible solution with respect to the comfortable shifting, durability and cost optimization.

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